R&D ON FUTURE ACCELERATORS AT FERMILAB

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OUTLINE

I. The frontier accelerators of today

II. The future contenders and Fermilab's role

III. Judging the contenders?

IV. Summary

R&D ON FUTURE ACCELERATORS AT FERMILAB

The total accelerator R&D program at Fermilab covers a very large number of areas

- R&D aimed at improved Tevatron performance
- R&D in support of our two neutrino projects
- R&D in support of the US LHC accelerator project
- R&D aimed at a 120 GeV fixed target program during the LHC era.
- Non-program directed R&D
- R&D aimed at identifying a future forefront accelerator facility that could be built at Fermilab in support of the U.S. HEP research program

This presentation will specifically cover only the last bullet.

Motivation

"Our goal is to build the next collider on the energy frontier here at Fermilab. Unlike 15 years ago in this country, there is not yet a clear consensus in the field on what that facility will be. So we must play a leading role in research and development on accelerators for the future. . . "

THE FRONTIER ACCELERATORS OF TODAY

The energy frontier is defined by the maximum center-of-mass energy (of the interacting constituents) achievable with current technology.

- Roughly speaking, lepton colliders have a factor of 5-10 comparative advantage over hadron colliders because all the energy is carried by a single consituent.

The energy frontier currently resides at Fermilab, where the Tevatron collider provides collisions of protons and antiprotons at 1.8 TeV (soon to be 2.0 TeV) in the center-of-mass.

- Nearest current competition is from LEP, with electron-positron collisions at 200 GeV in the center-of-mass and with operations scheduled to cease on 9/30/00.
- Upon completion of the LHC in 2005 the energy frontier will move to CERN.

Fundamental Limitations of Existing Frontier Machines

The fundamental limit on energy reach achievable in colliders depends on the particles accelerated.

Hadron colliders are limited by real estate and the bending field available:

$$\boxed{E_{CM}(TeV) = 0.6 \times B(Tesla) \times R(km) \times PF}$$

Examples:		
	R=1 km	R=25 km
	B=4.4 Tesla	B=8.3 Tesla
	PF=75%	PF=80%
	E_{CM}=2 TeV	E_{CM}=100 TeV

> The energy of a hadron collider is maximized by increasing the product of the radius times the magnetic field.

Circular electron-positron colliders are limited by beam power:

$$E_{CM}(GeV) = 146 \times \left| \frac{C(km) \times PF \times \Delta\nu_y}{L(10^{30}\,cm^{-2}sec^{-1})} \times \frac{P_b(MW)}{\beta_y^*(m)} \right|^{1/3}$$

Example:	R=4.2 km	R=100 km
	B=.075 Tesla	B=.008 Tesla
	U=3.0 GeV/turn	U=4.9 GeV/turn
	$\Delta\nu_y$=.075	$\Delta\nu_y$=.075
	β^*_y=0.1 m	β^*_y=0.1 m
	PF=0.7	PF=0.7
	L=1×10^{32}	L=5×10^{33} cm^{-2}sec^{-1}
	P_b=18.4 MW	P_b=607 MW
	E_{CM}=200 GeV	E_{CM}=500 GeV

The energy of a circular electron-positron collider is maximized by increasing the circumference, increasing the beam power, and/or decreasing the β^*.

The limitations inherent in the above expressions have led to the development of the **electron-positron linear collider** and the conceptualization of a **muon collider.**

Linear electron-positron colliders are limited by beam power:

$$\boxed{E_{CM}(GeV) = \frac{H_D}{6.4\pi L(10^{30}cm^{-2}sec^{-1})} \times \frac{N}{\sigma_x(nm)} \times \frac{P_b(MW)}{\sigma_y(nm)}}$$

Example:	H_D=1	H_D=1.4
	$N=3.3\times10^{10}$	$N=1.0\times10^{10}$
	P_b=.063 MW	P_b=9 MW
	σ_x=1500 nm	σ_x=330 nm
	σ_y=700 nm	σ_y=5 nm
	$L=1.0\times10^{30}$	$L=7.5\times10^{33}$ $cm^{-2}sec^{-1}$
	E_{CM}=100 GeV	E_{CM}=500 GeV

The energy of a linear electron-positron collider is maximized by increasing the beam power and/or decreasing the beam size.

The limitations inherent in the above expression have led to consideration of the possibility of a **muon collider.**

THE FUTURE CONTENDERS

Candidates for the next high energy facility to initiate operations after LHC currently include:

- A second generation electron-positron linear collider, or
- A first generation muon storage ring (or collider), or
- A fourth generation hadron (proton-proton) collider

The range of interesting center-of-mass energies:

e^+e^- (or $\mu^+\mu^-$)	<500 GeV	(Process specific)
	1.5 TeV	(LHC complementary)
	>4 TeV	(Frontier)
$\mu\rightarrow\nu$	20-50 GeV	(Process specific)
pp	30-100 TeV	(Frontier)

Fermilab has initiated efforts on each of these possible machines. Each faces different technological (and political) challenges and each is in a different state of development.

The Muon Storage Ring, or Collider, would fit on the Fermilab site. A linear collider or high energy hadron collider would not.

Design Issues

Most design issues are driven by the inverse square relationship between interaction cross sections and center of mass energy each of these colliders must achieve luminosities in the range **10^{33-34}cm^{-2}sec^{-1}.**

Linear Collider

$$L = \frac{f_{rep} n_b N^2}{4\pi\sigma_x\sigma_y} H_D = \frac{P_b N H_D}{4\pi E_{CM}\sigma_x\sigma_y}$$

High luminosity requires high beam power and small beam size. Furthermore, all other things being equal if the luminosity scales as E^2 then the beam power scales as $E^{2.5}$ (but circular machines are even worse, E^5!)

Hadron Collider

$$L = \frac{f_{rev} n_b N^2}{4\pi\sigma_x\sigma_y}$$

High luminosity is achieved by maximizing N and minimizing the beam size. Luminosities in the range of 10^{34} cm^{-2}sec^{-1} should be achievable based on straight-forward extrapolation from the LHC. Beam power is minimal but stored energy is very large.

Muon Collider

$$L = \frac{f_{rev} n_b \langle N^2 \rangle}{4\pi\sigma_x\sigma_y} = \frac{f_{rev} n_b N_0^2}{4\pi\sigma_x\sigma_y} \times \frac{\gamma\tau f_{rep}}{2}(1 - e^{-\frac{2}{\gamma\tau f_{rep}}})$$
$$= \frac{f_{rev}\langle N_{tot}^2 \rangle}{4\pi\sigma_x\sigma_y n_b}$$

Quite a number of considerations are required in designing to high luminosity:

1. Since we want the most luminosity per muon produced we would like to choose n_b=1.
2. The pulse repetition rate should be comparable to $\gamma\tau$. For a 1 TeV muon this is 20msec (50 Hz).
3. The revolution frequency of the collider should be as large as possible. This means the circumference should be as small as possible, i.e. the magnetic bend field should be as large as possible.
4. Small beam sizes at the interation point are essential. This means low β and low beam emittance.

As in case of e+e- the beam power is large and scaling as E^{2-3} to maintain a luminosity rising as the square of the energy.

A SECOND GENERATION LINEAR COLLIDER

Pre-conceptual designs exist for an electron-positron linear collider operating in the range 500-1000 GeV (center-of-mass) based on room temperature (SLAC, KEK) and superconducting (DESY) accelerating structures.

Primary Components (see picture)

- Particle source/injector
- Main accelerating linac
- Beam delivery/final focus

Energy

Room temperature design operates at 11 GHz and provides an acceleration field of 50 MV/meter.

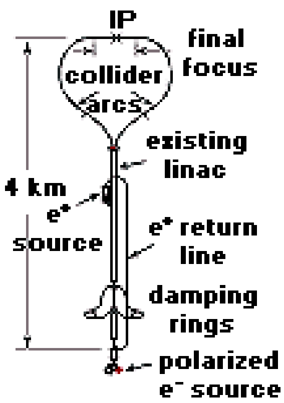
20 km of linac per 1000 GeV of energy

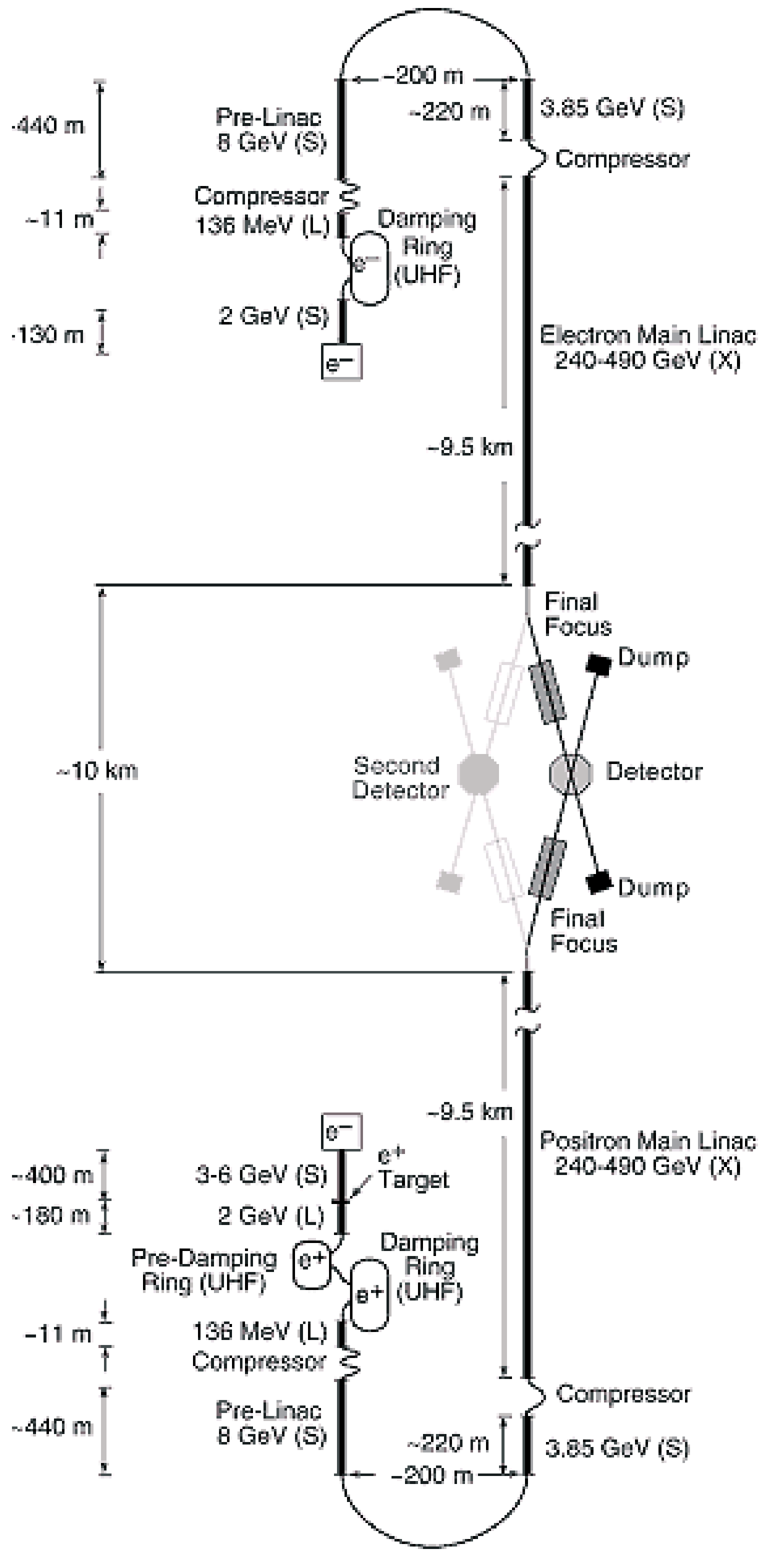
Superconducting design operates at 1.3 GHz and provides an acceleration field of 25 MV/meter.

20 km of linac per 500 GeV of energy, or

20 km of linac per 800 GeV of energy @ 40MV/m

SLC 100 GeV	NLC 0.5 - 1.5 TeV





Critical Technologies & Issues

- Accelerating gradient: 25-50 MeV/m
  - RF generation and distribution
  - Peak power
- Creation of very small emittance/high brightness beams: 3 mm-mrad
  - Beam sources
  - Damping rings
- Preservation of a very small emittance: 4 mm-mrad
  - Wakefields
  - Mechanical tolerances
  - Beam-based alignment and feedback
- Optical aberrations: 5 nm spot size
- Beam jitter: 5 nm spot size
  - Ground motion
  - Tuning algorithms
- Machine component protection: 5-10 MW beam power
  - Collimators
  - Machine protection system
- Total cost
- Public outreach
  - Minimize surface presence

Fermilab Role

Fermilab has signed an MOU with SLAC to pursue pre-conceptual R&D through the period leading up to the authorization to prepare a conceptual design report. Our efforts are being coordinated by Tom Dombeck with participation of the Beams, Technical, FESS, ES&H Divisions/Sections.

Identified areas of Fermilab lead

- Main Linac (Technical and Beams Division)
  - includes everything downstream of the rf pulse compression
  - includes industrialization of structure fabrication. Need to figure out how to build (and assemble into modules) 1,200,000 of these (↓) without breaking the bank, or taking forever.

- Fermilab Site Study (FESS and all Div/Secs)

  A Fermilab Committee for Site Studies has been formed to coordinate activities related to the siting of **any new accelerator** that could be built on-or-near the Fermilab site. This committee is charged to

  - Categorize the geology of northeastern Illinois.
  - Evaluate civil construction requirements and methods.
  - Identify possible sites for linear colliders, large hadron colliders, and muon facilities.
  - Consider all associated ES&H issues.
  - Minimize surface impacts.
  - Identify external interests that will be affected by plans for future Fermilab facilities and develop a public outreach program.

Under the aegis of this committee two sets of sites and methodologies for constructing an NLC at Fermilab are being explored:

- North-south orientation in a deep tunnel, with the interaction area and a common injector on the east side of the Fermilab site.
- East-west orientation in a cut and cover tunnel, not contiguous with Fermilab and with separate injectors at each end.

Identified Areas of Fermilab Support

- Accelerator physics (Beam Physics)
  - Beam transport and tuning.
  - Wakefields and emittance preservation.
  - Structures
- Permanent Magnets (Beams/Technical Division)
  - Performance requirements and designs for the linac beam transport system.
- RF and timing synchronization (RF&I Department)
  - Timing system development

A FIRST GENERATION MUON STORAGE RING

Design concepts have been developed for a muon collider and an R&D program initiated. If it could be made to work a Muon Collider would offer significant advantages over an electron collider:

- (Relative) absence of synchrotron radiation allows application of circular storage ring technology.
- Energy expandability is relatively straight forward
- Lack of synchroton radiation in interaction gives much better defined center-or-mass energy
- Cross section for direct production of Higgs is $(m_\mu/m_e)^2$ higher than for electron-positron collider.
- Fits on the Fermilab site

BUT

The muon lifetime is 2.2 μsec!

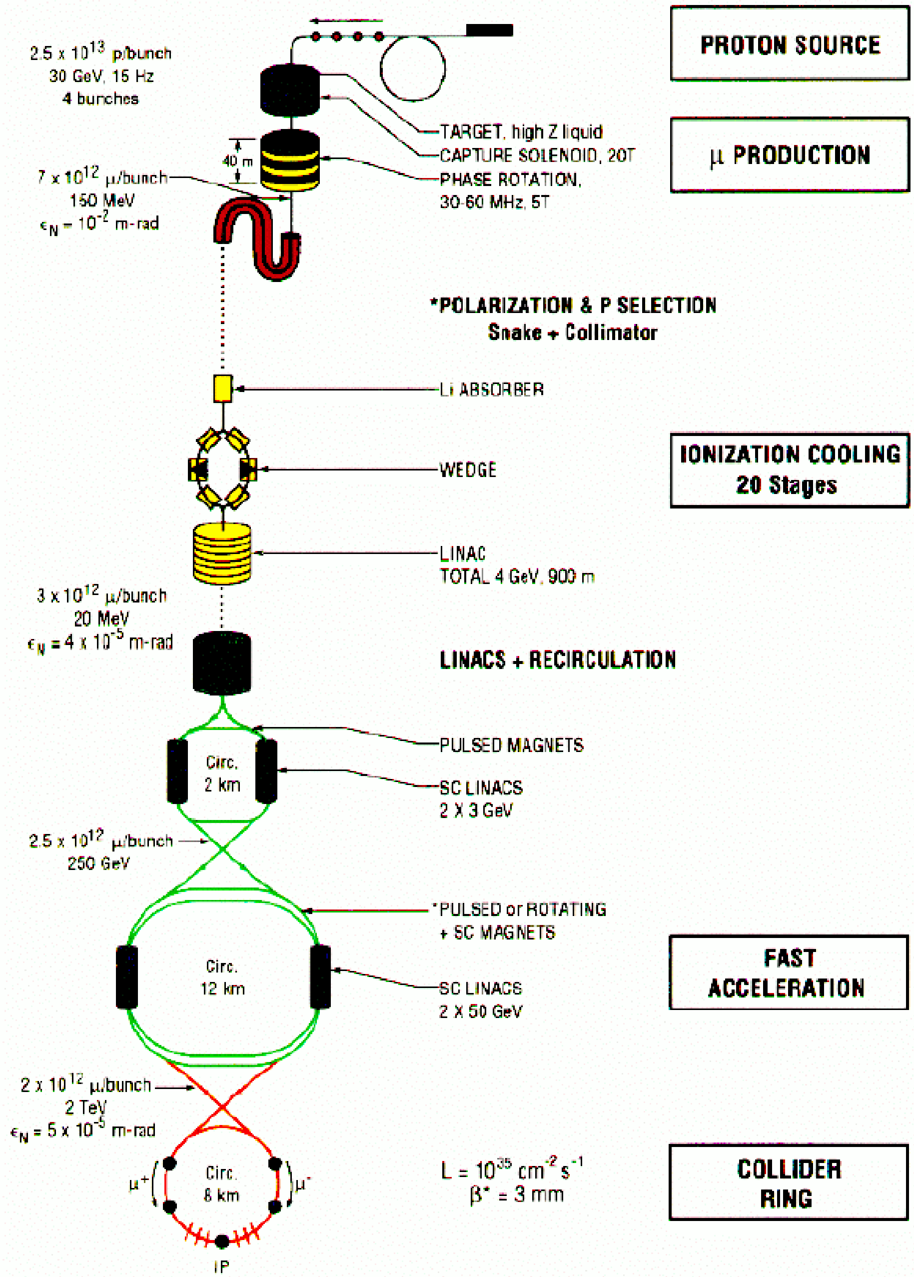
AND

As a secondary beam, the emittance is huge!

Muons must be collected, cooled, and accelerated quickly.

Primary Components (see picture)

- Muon source
- Muon cooling
- Muon acceleration
- Collider ring


PROTON SOURCE
μ PRODUCTION
IONIZATION COOLING
20 Stages
FAST
ACCELERATION
COLLIDER
RING
2.5 x 10^13 p/bunch
30 GeV, 15 Hz
4 bunches
TARGET, high Z liquid
CAPTURE SOLENOID, 20T
PHASE ROTATION,
30-60 MHz, 5T
40 m
7 x 10^12 μ/bunch
150 MeV
ε_N = 10^-2 m-rad
*POLARIZATION & P SELECTION
Snake + Collimator
Li ABSORBER
WEDGE
LINAC
TOTAL 4 GeV, 900 m
3 x 10^12 μ/bunch
20 MeV
ε_N = 4 x 10^-5 m-rad
LINACS + RECIRCULATION
PULSED MAGNETS
Circ.
2 km
SC LINACS
2 X 3 GeV
2.5 x 10^12 μ/bunch
250 GeV
*PULSED or ROTATING
+ SC MAGNETS
Circ.
12 km
SC LINACS
2 X 50 GeV
2 x 10^12 μ/bunch
2 TeV
ε_N = 5 x 10^-5 m-rad
μ+
Circ.
8 km
μ-
IP
L = 10^35 cm^-2 s^-1
β* = 3 mm

Critical Technologies and Issues

- Proton source: 4 MW on target (2 x SNS)
  - 5x10^{13} protons in a 1 nsec bunch
  - Radiation and activation
- Muon production/capture: μ/p = 1:10
  - Solenoids in high radiation fields
  - rf in high radiation and magnetic fields
- Ionization cooling: 10^{-6} reduction in phase space
  - rf in high magnetic fields
  - Simulations
  - Experiments
- Acceleration: Average gradient of 2.5 MV/m
  - Gradients
  - Recirculating linacs
- Muon decays: 3x10^{13} decays/second
  - SC magnet heat load
  - Detector background
  - Neutrino radiation
- Total Cost: $??

This is all pretty tough. This is why we have fallen back to consideration of a muon storage ring.

Almost all the base technologies are the same but performance levels are relaxed;

- Proton source: Power/4, charge per bunch/100
- Muon production/capture: Still μ/p = 1:10
- Cooling: Relaxed by 10^{-4}
- Acceleration: Still ~2 MV/m, but there's less of it
- Muon decays: Still fewx10^{13}/second, but now they're providing physics(!) Neutrino radiation reduced but still requires attention.
- Storage ring: no IP
- Total Cost: <$??

Fermilab Role

R&D in support of a Muon Collider or Storage Ring is organized as a national collaboration with Fermilab, BNL, and LBNL as the lead labs, and with signficant university involvement. Most activities are coordinated by the Muon Collaboration with the laboratories acting in support. The laboratories have convened a Muon Technical Advisory Committee (MUTAC) to offer advice on the R&D program.

Fermilab specific activities within the prgram include:

Neutrino Factory Study

Norbert Holtkamp is leading a design feasibility study for a neutrino factory based on a muon storage ring.

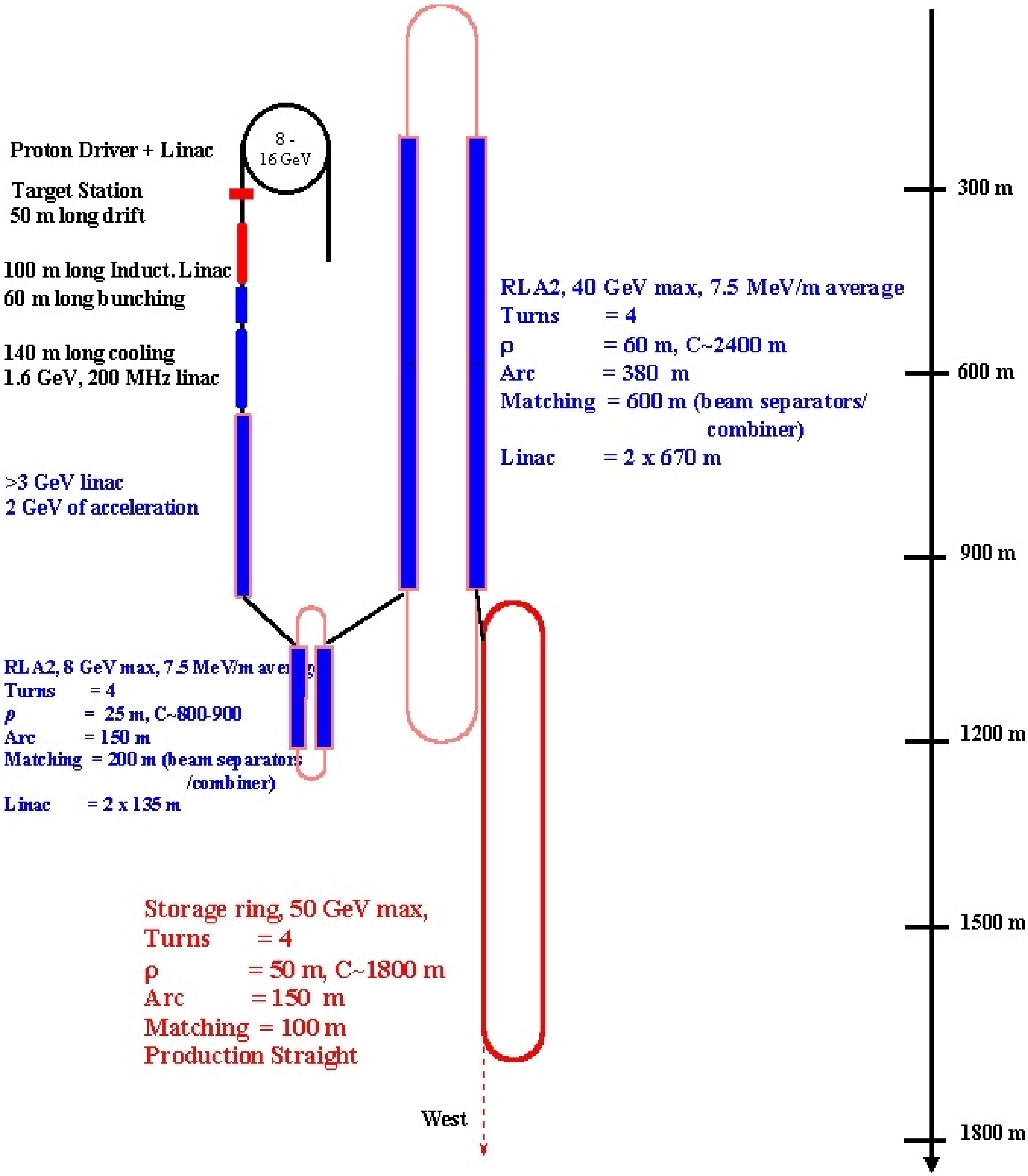
Charge (from Fermilab Director)

- A design concept for a muon storage ring facility
- Identification of the likely cost drivers.
- Identification of the requried R&D program.
- Identification of any specific environmental, safety, and health issues.

Report due March 2000.

Preliminary Parameter list

Energy	50	GeV
Decay Ratio	40	%
Emittance	3200	mm-mrad
Muons/pulse	2x1012	
Repetition rate	15 Hz	
Typical muon decay angle	2.0	mrad
Muon beam divergence	0.2	mrad

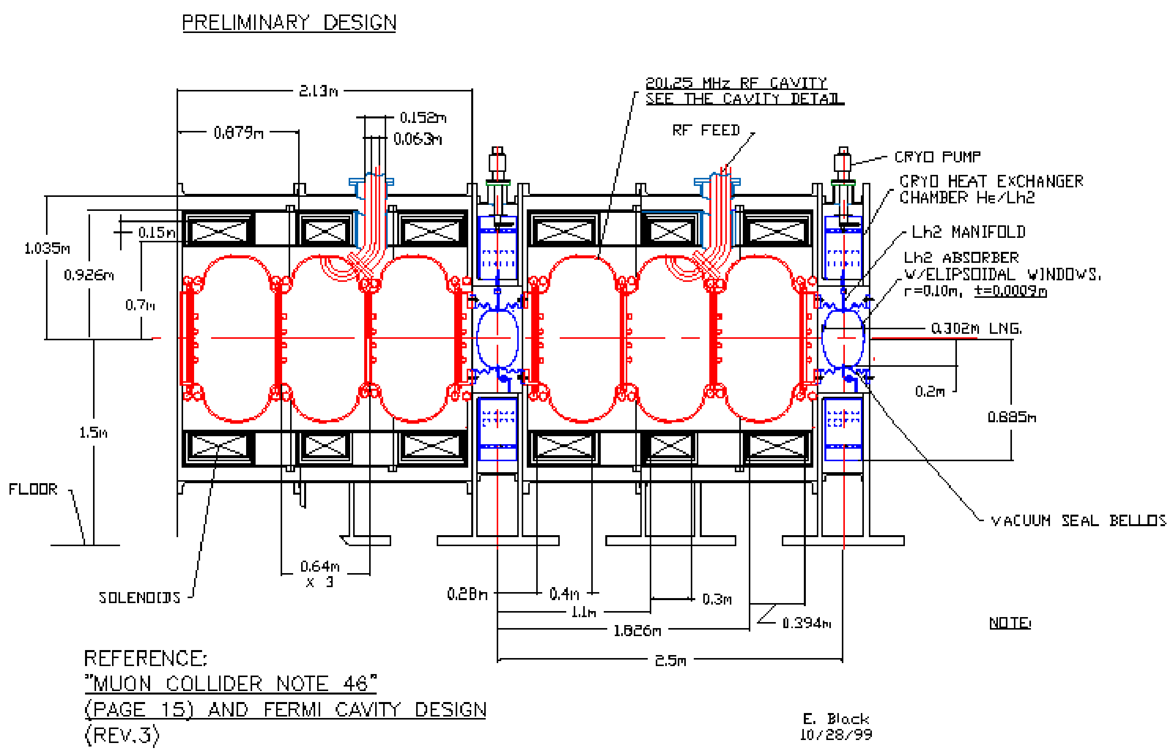


8 - 16 GeV
Proton Driver + Linac
Target Station
50 m long drift
100 m long Induct. Linac
60 m long bunching
140 m long cooling
1.6 GeV, 200 MHz linac
>3 GeV linac
2 GeV of acceleration
RLA2, 40 GeV max, 7.5 MeV/m average
Turns = 4
ρ = 60 m, C~2400 m
Arc = 380 m
Matching = 600 m (beam separators/ combiner)
Linac = 2 x 670 m
RLA2, 8 GeV max, 7.5 MeV/m
Turns = 4
ρ = 25 m, C~800-900
Arc = 150 m
Matching = 200 m (beam separators /combiner)
Linac = 2 x 135 m
Storage ring, 50 GeV max,
Turns = 4
ρ = 50 m, C~1800 m
Arc = 150 m
Matching = 100 m
Production Straight
West
300 m
600 m
900 m
1200 m
1500 m
1800 m

Muon Cooling Experiment (MuCool)

Goal is verification of cooling simulations by measuring the single pass map of a muon through a cooling section. Experiment being recast in light of Neutrino Factory .

- LH2 module design by IIT
- 805 MHz test set up at Lab G (Fermilab)
- 805/200 MHz cavity design by Fermilab and LBL
- Simulations by Fermilab (Computing Division)
- Experiment detector design coordinated by Fermilab (Steve Geer spokesperson)



A FOURTH GENERATION HADRON COLLIDER

The technology to produce a proton-proton collider with an energy a factor of seven beyond the LHC (a factor of 50 beyond the Tevatron) exists. The problem is that simply scaling up from the Tevatron or LHC creates a facility that is too expensive.

Study of a hadron collider operating with a center-of-mass energy of 100 TeV has been underway since the 1996 Snowmass meeting. Two approaches are being pursued based on:

- High field (>10 T) magnets, and
- Low field (<2 T) magnets

These two approaches are distinguished by the role of synchroton radiation and by the physical size of the collider.

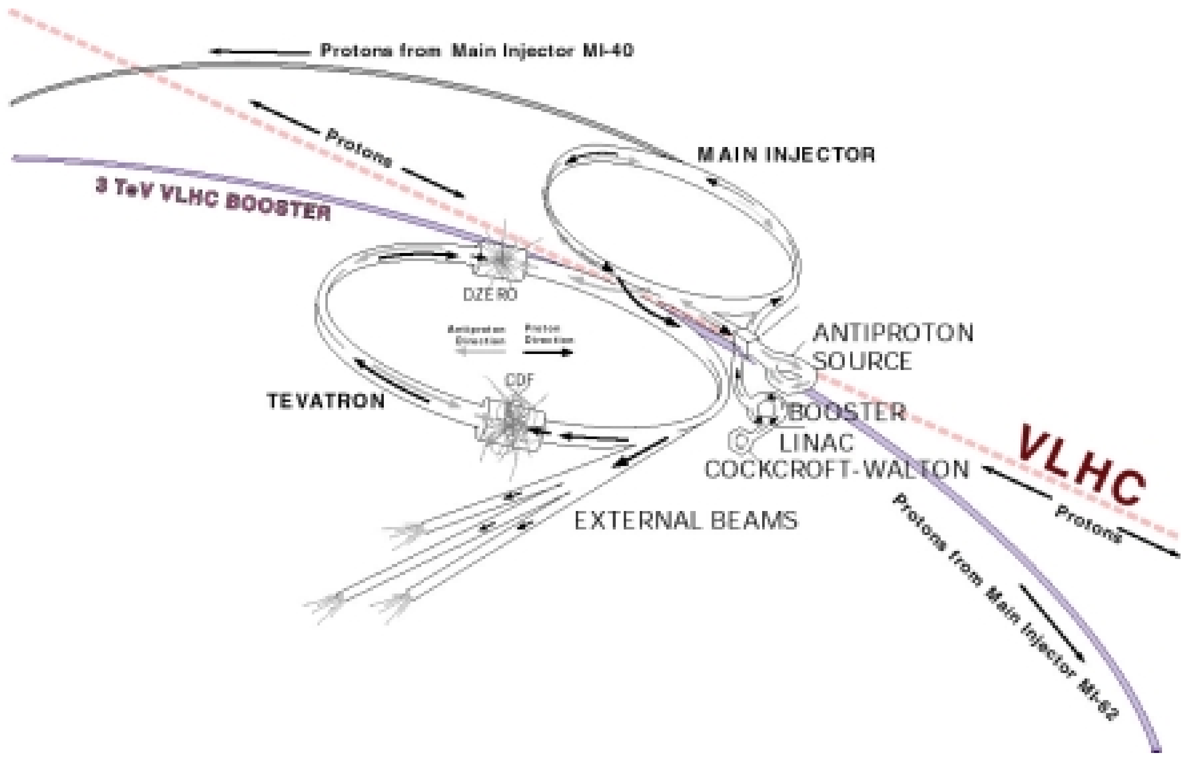
A 100 TeV collider based on a 12 T dipole would have a circumference of approximately 100 km.

A 100 TeV collider based on a 2 T dipole would have a circumference of approximately 600 km.

Components (see picture)

- Particle source/injector

- Collider ring



Critical Technologies and Issues

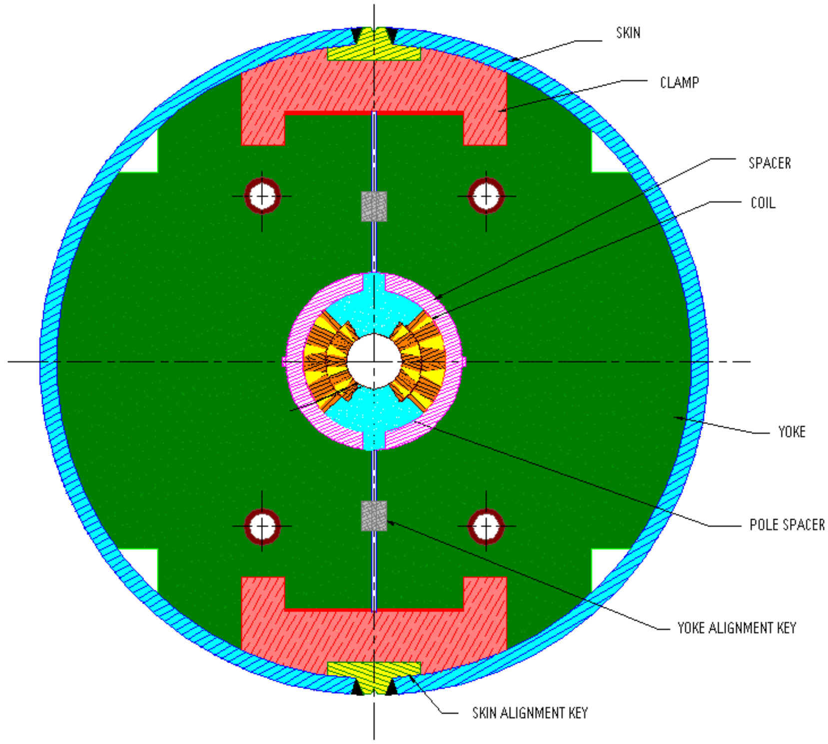
- Magnet cost: $250/T-m
  - Low field magnet
  - High field cosθ
  - High field novel designs
  - HTS
- Synchrotoron Radiation
  - Is it a help or a hinderance?
- Emittance preservation
  - Vibrations and noise
- Installation and maintenance
- Tunnel cost and utility distribution: $1000/m+utilities
  - Geology
  - Minimizing surface presence
- Beam stored energy: 1-10 GJ
  - Machine protection
  - Radioactivation of soils and/or water
- Optimum bunch spacing
  - Trade off between stored energy and interactions/crossing
- Total cost
- Public outreach

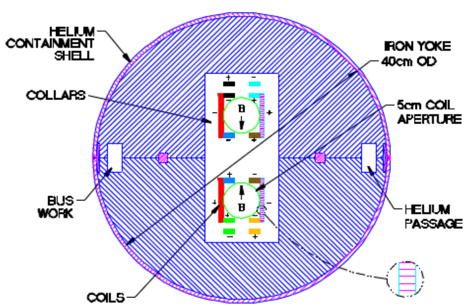
Fermilab Role

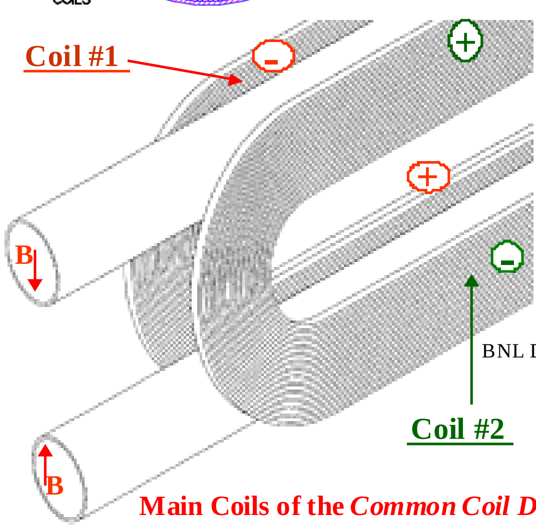
The VLHC effort is organized as a national collaboration with Fermilab, BNL, LBNL, and Cornell as the lead labs. A steering committee exists with representation of the above institutions plus SLAC. This organization sponsors workshops and an annual meeting. Fermilab specific activities include:

High Field Magnet R&D

- 12 Tesla Nb_3Sn $\cos\theta$ magnet.
  - FY00 goal is fabrication of a short magnet coil and cold mass this summer, complete model magnet in FY01.
- 12 Tesla common coil magnet.
  - FY00 goal is to wind practice coils while
  - TD will start winding practice coils this spring (common coil magnet)
- Conductor R&D
  - A superconducting materials program is being managed jointly by LBNL, Fermilab, and BNL, supported directly by the DOE.







BNL Drawing

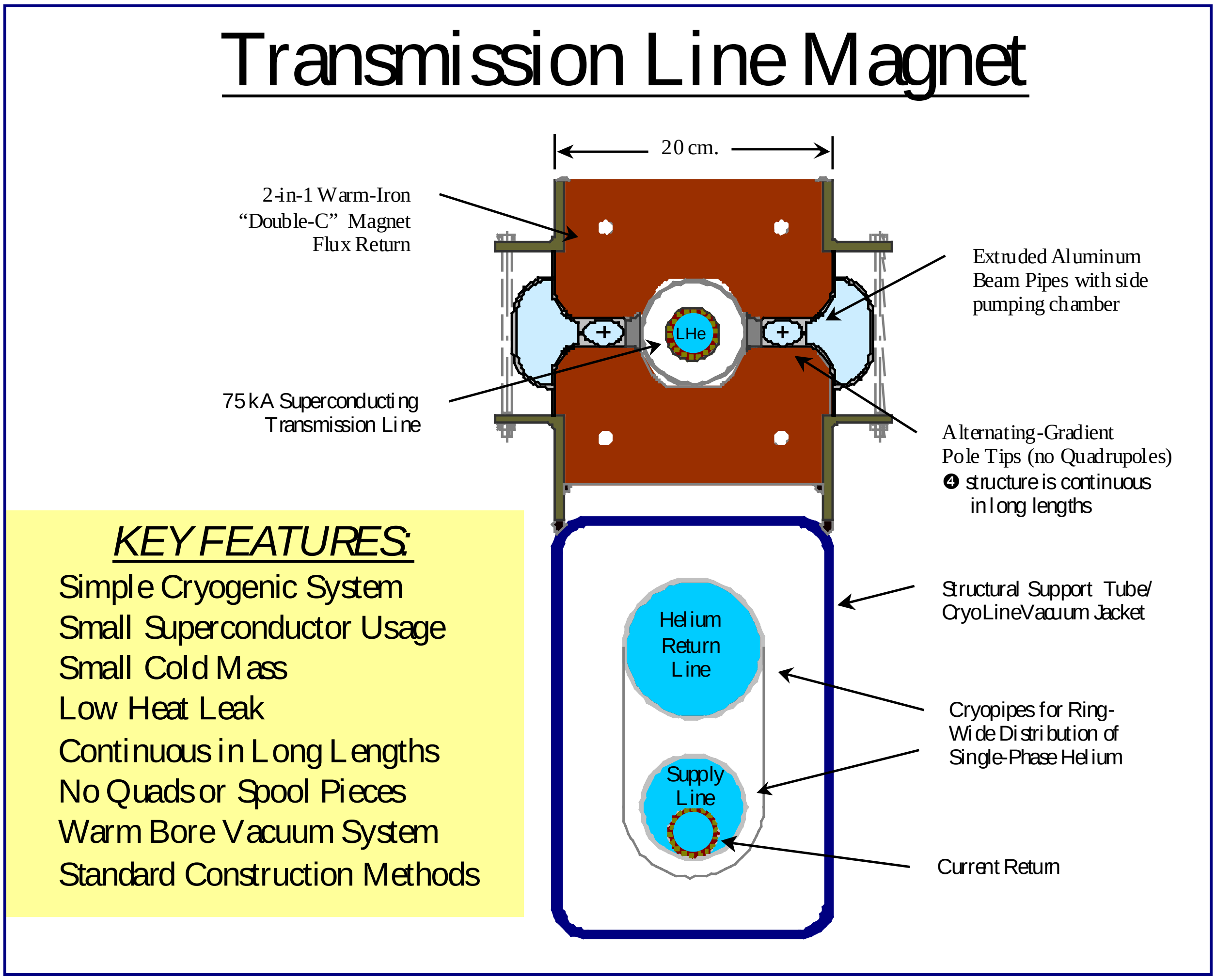
Main Coils of the *Common Coil Design*

Common Coil Design
(The Original Concept)

- **Simple 2-d geometry with large bend radius (no complex 3-d ends)**
- **Conductor friendly (suitable for brittle materials - most are, including HTS tapes and cables)**
- **Compact (compared to single aperture D20 magnet, half the yoke size for two apertures)**
- **Block design (for large Lorentz forces at high fields)**
- **Efficient and methodical R&D due to simple & modular design**
- **Minimum requirements on big expensive tooling and labor**
- **Lower cost magnets expected**

Low Field Magnet R&D

- An advanced design concept exists for a 2 T "superferric" magnet based on NbTi.



- 100 kA has been achieved in the test loop at MW-9.
  - Studies of quench behavior of NbTi cable underway
  - Goal is to construct a 50 m test at MW-9 over next two years.

Construction Studies

A construction study for a 3 TeV injector is identifying many issues related to building a VLHC in the vicinity of Fermilab.

Siting studies related to the larger ring(s) are being done under the umbrella of the Fermilab Site Studies Committee.

		LEPTONS					HADRONS		
		Linear			Circular				
	NLC	TESLA	CLIC	Muon Collider	VLEPC	VLCH (Low Field)	VLHC (High Field)		
E_{CM}	**500**	**500**	**3000**	**3000**	**500**	**100000**	**100000**	**GeV**
E_{CM} (constituent)	500	500	3000	3000	500	10000	10000	GeV
Rep rate	120	5	100	15	1.E-04	1.20E-05	1.20E-05	Hz
Revolution frequency					464	464	2769	
Bunches/pulse	95	2820	154	1	100	129240	20794	
Particles/bunch	1.0E+10	2.0E+10	4.0E+09	2.0E+12	1.2E+12	9.4E+09	5.0E+09	
Average Accelerating Gradient	50	25	150	3		3.00E-04	5.00E-05	MeV/m
I_{AV}	18	45	10	5	9206	90191	46063	μA
Beam Power (Total)	9	23	30	14	1415			MW
Stored Energy (per beam)						9719	832	MJ
σ_H (at IP)	330	553	43	3000	64500	2000	2000	nm
σ_V (at IP)	5	5	1	3000	1777	2000	2000	nm
H_D	1.4	1.4	2.1	785	1	1	4	
Luminosity	**8.E+33**	**2.E+34**	**1.E+35**	**4.E+34**	**5.E+33**	**1.E+34**	**1.E+34**	**cm^{-2} sec^{-1}**

Notes:

All the lepton colliders have large beam power (and correspondingly large site power)

Hadron colliders have large stored energy

Muon and hadron colliders have "big" (few μm) beams

HOW WILL THE CONTENDERS BE JUDGED?

It is not know at present exactly how a choice will be made from among the contenders. However, any decision will presumably be based on consideration of

- Physics goals and the best indications of the day as to the energy scale of interest
- Technical feasibility
- Cost
- The intentions/actions of other countries
- The funding environment at the time
- Public acceptance

I believe that we are currently in the information gathering, not the decision making, phase. However, we have certain constraints, and an important question to answer is "Can Fermilab, or the U.S. for that matter, sustain parallel efforts in all these directions?"

- My guess is that it would require ~$20M/year for NLC or MSR to develop a real construction plan over the next several years. VLHC may be less because the range of new technlogies required is less broad.

-> We are going to have to start consolidating effort sooner rather than later.

Specific questions that each of the contenders are going to have to answer:

Everyone

- Can it be constructed as a series of <$3-4B/steps with a compelling physics program associated with each step?

  Our community is going to have to start thinking more than one step ahead.

- Will the (U.S. and international) HEP community support it?
- Will the government(s) support it?
- Will the local residents support it?
- Are “Critical Technologies and Issues” solvable via an affordable R&D program?
- How would the (international) effort to construct such a facility be organized?
- Can it be sited at an existing laboratory?

Linear Collider

What can be built for $\leq$ \$4B?

- When can this question be answered?
- Is any cost estimate believable before acceptable accelerating structures have been produced by industry?

If so what is it and is there a physics program?

- Has something come out of LEP or Run II that indicated the correct energy scale?
- (Or is U.S. community still wedded to 1.0-1.5 TeV?)
- Can a detector be built that will operate in this environment?

How do alternative technologies compare?

- How much effort should be invested in more strongly damped x-band designs?
- How does x-band compare to superconducting (or two beam)?

What are the upgrade paths?

- What energy could be realized as an upgrade?
- Is U.S. community still wedded to 1.0-1.5 TeV electrons, or would we rather take the next step (beyond 0.5 TeV) in the hadron or muon realm ?

- Can an upgrade path be defined before initiation of construction?

Is a circular collider really not an option?

- Critically dependent on desired energy/luminosity reach and upgrade path.

Bottom Line: Need to demonstrate a physics case, and a technology that can support a <$4B facility, with an identifiable upgrade path, probably by about 2002. (Includes resolution of room temperature vs. superconducting.)

Muon Collider/Storage Ring

Has the Muon Collider been ruled out as a choice for a construction project with a 201x construction start?

If so, can a Muon Storage Ring be built for ≤ $2B?

- How much is the community willing to ask, and the government willing to support, for a non-frontier facility?

If so, what is the physics program?

- What is the true breadth of the physics program beyond neutrino oscillations?

When could something actually be proposed?

- Is a Muon Storage Ring a competitor to NLC, TESLA, and/or VLHC or not?
- What is the required R&D program, how much does it cost, and when could it be completed?

To what extent does the Neutrino Source really provide a test bed for Muon Collider technologies?

Is a Muon Collider the desired upgrade step?

Bottom Line: Need to demonstrate a physics case, and identify potential technologies that can achieve this for <$2B probably by about 2002, with technology demonstration and upgrade path by about 2005.

VLHC

Can something be built for ≤ $4B?

- When can this question be answered?
- How long would it take to produce a design report once this is the identified path?

If so, what is it and is there a physics program?

- Can a program be defined before LHC runs?
- What is the minimum useful energy step relative to LHC?
- Can a detector be built that will operate in this environment?

Is there a (cost) optimum magnetic field?

- What is the basis for a high/low/medium choice?

Is synchrotron radiation worth it?

- Is radiation damping really going to work in this ring once all things are considered?

How does one protect the machine from itself?

What are the upgrade paths?

- What energy would the community like to see in 202x in a hadron collider?

What are technically required demonstration projects?

Bottom Line: Need to demonstrate a physics case, and identify a technology that can achieve this for <$4B by about 2002, with technical demonstration and an identifiable upgrade path by about 2005.

I leave as an exercise for the listener consideration of how to proceed if we find ourselves in the happy situation that multiple facilities meet all required criteria.

Scenarios for consideration

350 GeV x-band linear collider -> 1000 GeV uprade -> 4 TeV two beam linear collider

350 GeV circular electron collider -> 30 TeV low field pp -> 180 TeV high field pp

28 TeV low field pp -> 170 TeV high field pp

20 GeV muon storage ring -> 50 GeV muon storage ring -> 100-1000 GeV muon collider

500 GeV superconducing linear collider -> 1 TeV muon collider

Everyone should feel free to go out and invent their own scenario. (There are lots of them).

SUMMARY & INSPIRATION

Three approaches to a new forefront high energy physics facility for the post-LHC era are under study. Each of these is in a different state of readiness and faces different challenges. I would claim that none are viable at the moment, but that's OK—that's why we do R&D. The challenge is to develop a viable candidate(s) before the start of LHC operations.

- VLHC has a realizable technology for a frontier facility . . . that is prohibitively expensive if extrapolated a factor of 5-10 beyond LHC.

  Emphasis is on new technologies that can significantly reduce the cost per TeV.

- Muon collider/storage ring has an unvalidated technology base. However, it has potential for providing a frontier machine in the post-LHC era with an opportunity for a phased implementation. Cost is not well known.

  Emphasis is on invention and validation of supporting technologies, and staging.

- NLC has an advanced technological base . . . for an energy reach that is comparable to that of LHC and at a currently estimated cost that is prohibitive. Technologies for an energy reach well beyond LHC are not yet identified.

  Emphasis is on R&D aimed at supporting conceptual designs and reduction of costs. Opportunities exist for R&D into new technologies that can provide a true frontier capability.

What can Fermilab do?

Educate ourselves in all three realms.

Be willing to take a critical view on the physics, costs , and technologies of all options.

- Deemphasize routes that appear not to be effective as soon as this becomes evident.

Think hard about staging.

- Although the climate may change in the future, it is difficult to imagine the government supporting a facility in excess of ~$4B in the intermediate future.

Form a vision for ourselves and discuss with the HEP community

What can the HEP community do?

Establish the criteria that any successful facility needs to meet.

Think through the issues-look more than one step ahead. (Look how well this has served CERN.)

Establish a goal of developing a coherent plan by ~2002 and then coalescing effort around this.

- Includes establishing mechanisms for comparative evaluations of technologies.

Share the work.

- The R&D effort associated with any one of these efforts will tax the limits of a single laboratory.

  ->coordinate efforts
- Develop interlaboratory understandings that there are not winners and losers—everyone is going to have to pitch in and build whatever we settle upon.
- Start developing models for interlaboratory and/or international collaboration.

High energy physics has always progressed in step with the extension of the energy frontier. The High Energy Physics community itself has historically led the effort to develop the new technologies that will support its future.

Opportunities still abound, but the stakes associated with each step grow larger with each generation as the scope, construction period, and costs grow. As a result it is ever more important to do the right thing.

I urge each of you to participate, even if you are not directly assigned, within the Fermilab R&D program and in the national discussion (debate) on our future. If you do not consider yourself an accelerator physicist, don't worry about it—you can contribute and the accelerator R&D project leaders will be glad to give you a job. . . .

After all, our future depends on it.